The NRO 2.4-m Opportunity:

Spectroscopy of Planets

Around the Nearest Stars

Geoff Marcy

NASA ExoPAG 7 Meeting

Long Beach, California

6 Jan 2013

Spectroscopy

The Key Diagnostic Technique in Astrophysics

* Planets in Solar System

* Stars

* Galaxies

* Interstellar medium

* High Redshift Galaxies

* Black Holes

Spectroscopy

The Key Diagnostic Technique in Astrophysics

* Planets in Solar System

* Stars

* Galaxies

* Interstellar medium

* High Redshift Galaxies

* Black Holes

- Chemical Composition
- Dynamics: Motions, Masses, Interactions
- Internal Physics: Rotation, Magnetic Fields

Spectroscopy

The Key Diagnostic Technique in Astrophysics

* Planets in Solar System

* Stars

* Galaxies

* Interstellar medium

* High Redshift Galaxies

* Black Holes

Spectroscopy:
Needed for Exoplanets

- Chemical Composition
- Dynamics: Motions, Masses, Interactions
- Internal Physics: Rotation, Magnetic Fields

AFTA-WFIRST:
2.4-m NRO Telescope

* *Astrophysics Focused Telescope Assets – WFIRST*

* Consider a version of WFIRST utilizing one of two 2.4-m NRO telescopes given to NASA.

* The committee, chosen by NASA HQ, is chaired by Neil Gehrels and David Spergel with prominent members from the dark energy, IR surveys and exoplanet communities

AFTA–WFIRST SDT meeing Nov 19–20 at Goddard.

AFTA-WFIRST:
2.4-m NRO Telescope

Groundswell of Arguments and Technical work:

A High Contrast Coronagraph

and Spectrometer

Imaging and Spectroscopy of Exoplanets

Proponents I'm aware of:

J.Trauger, M.Clampin, O.Guyon, B.Macintosh, D.Spergel,
J.Kasdin, T.Greene, D.Savransky
Exoplanet Exploration Program (G.Blackwell, R.Akeson, W.Traub)

AFTA-WFIRST:
2.4-m NRO Telescope

Groundswell of Arguments and Technical work:

A High Contrast Coronagraph

and Spectrometer

Imaging and Spectroscopy of Exoplanets

Questions:
1. Science Case: Are there resolvable planets?

AFTA-WFIRST:
2.4-m NRO Telescope

Groundswell of Arguments and Technical work:

A High Contrast Coronagraph

and Spectrometer

Imaging and Spectroscopy of Exoplanets

Questions:
1. Science Case: Are there resolvable planets?
2. Is Coronagraph technology Ready?

Groundswell of Arguments and Technical work:

A High Contrast Coronagraph

and Spectrometer

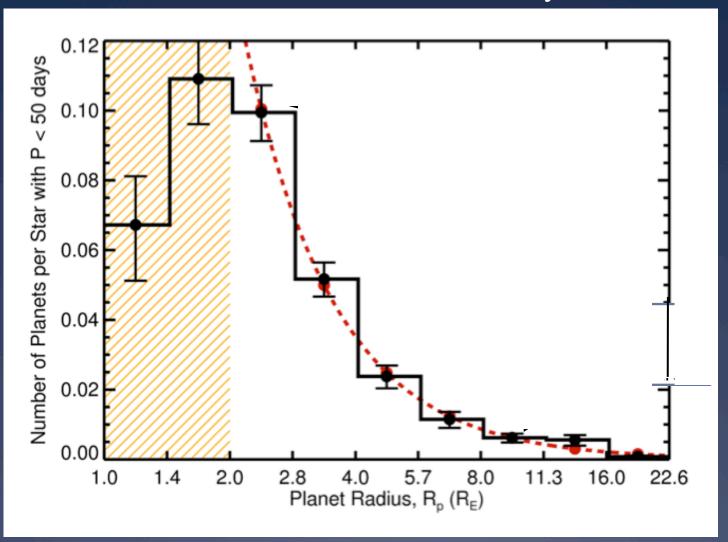Imaging and Spectroscopy of Exoplanets

Questions:
1. Science Case: Are there resolvable planets?
2. Is Coronagraph technology Ready?
3. Are the NRO telescope optics good enough ?

NASA *Kepler* Mission:
Occurrence of Planets

- Distribution with Planet Radius
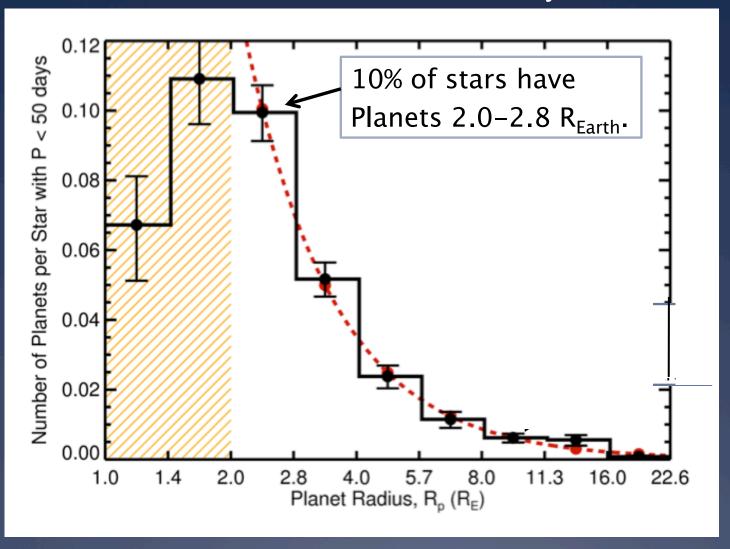- Distribution with Orbital Period

Distribution of Planet Radii
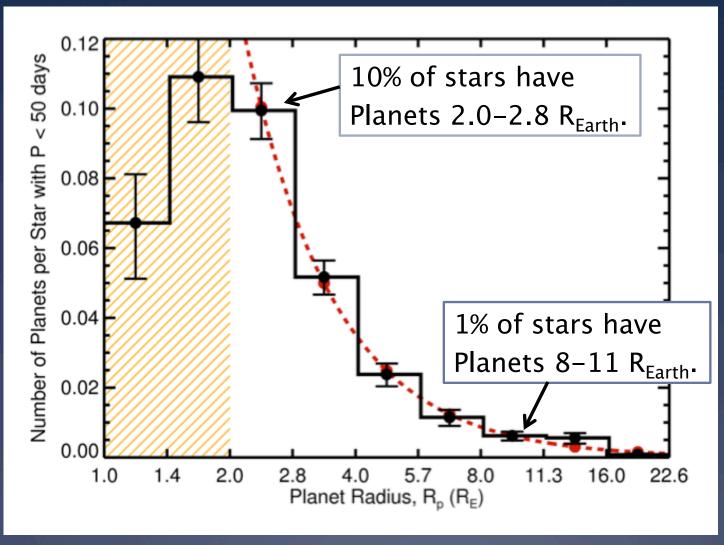## For Orbital Periods < 50 Days

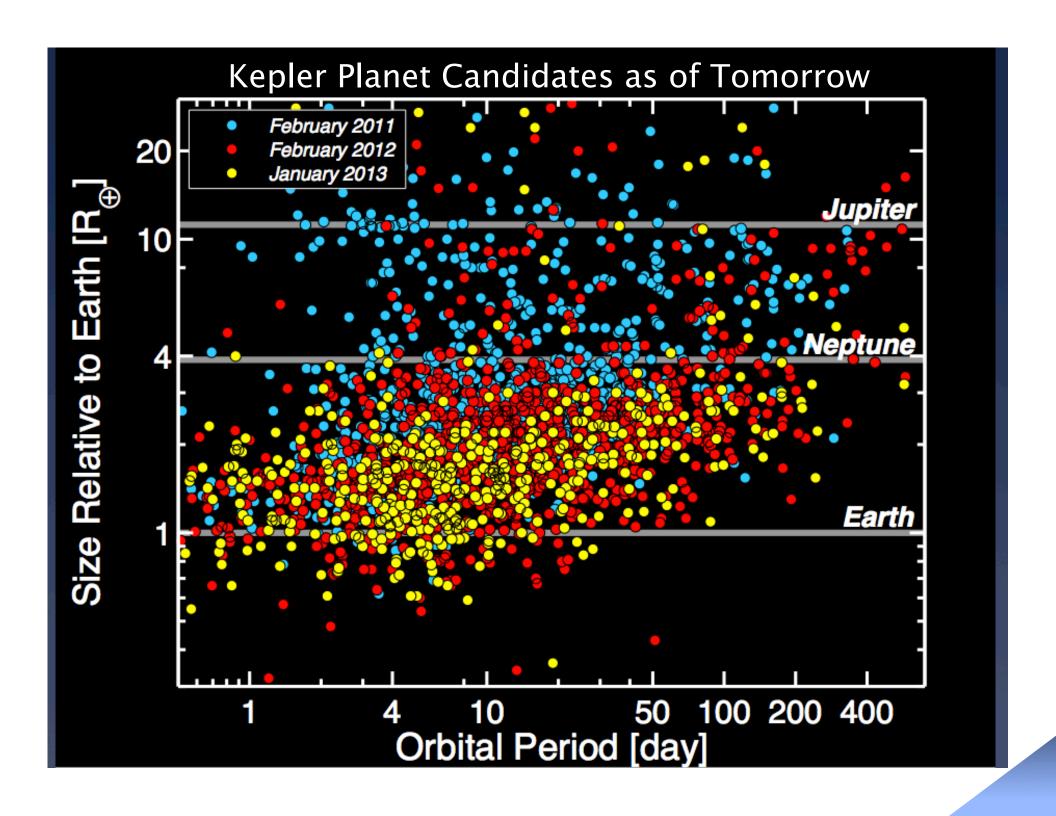Andrew Howard and Kepler Team, as of Sept. 2011

Distribution of Planet Radii
For Orbital Periods < 50 Days

10% of stars have Planets 2.0–2.8 R_{Earth}.

Andrew Howard and Kepler Team, as of Sept. 2011

Distribution of Planet Radii
For Orbital Periods < 50 Days

Andrew Howard and Kepler Team, as of Sept. 2011

Kepler Planet Candidates as of Tomorrow
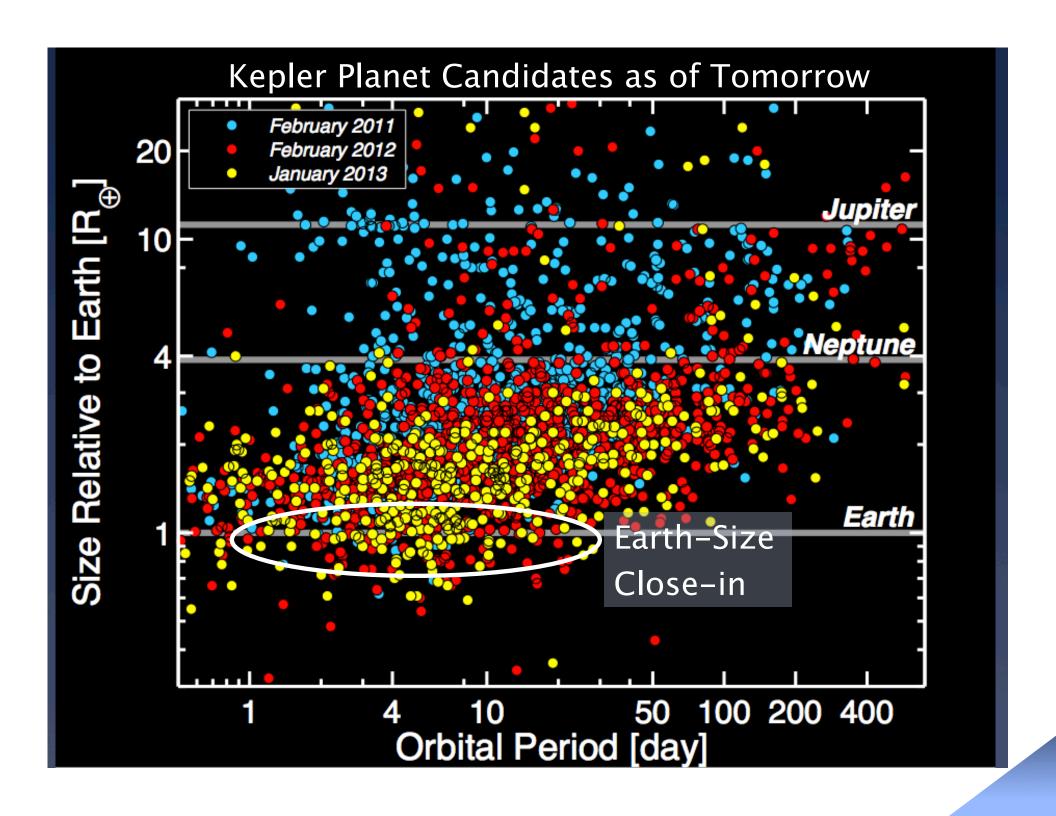
Occurrence with Planet Radius: Extension to 1.0 R$_{Earth}$

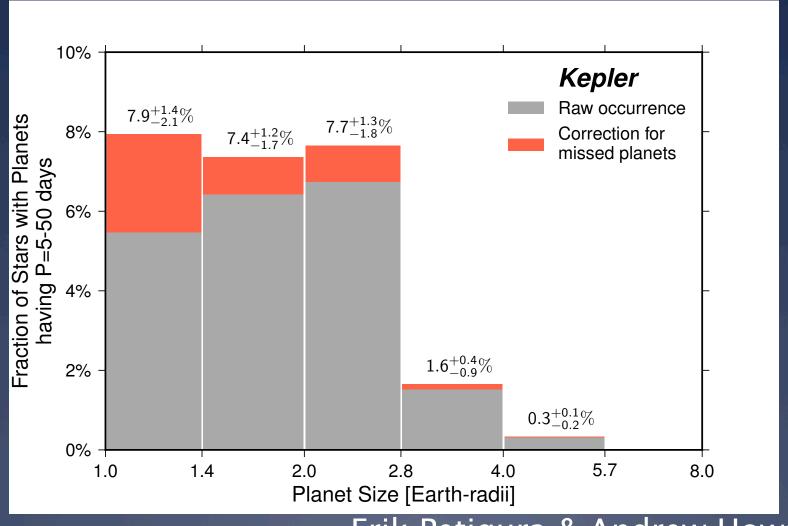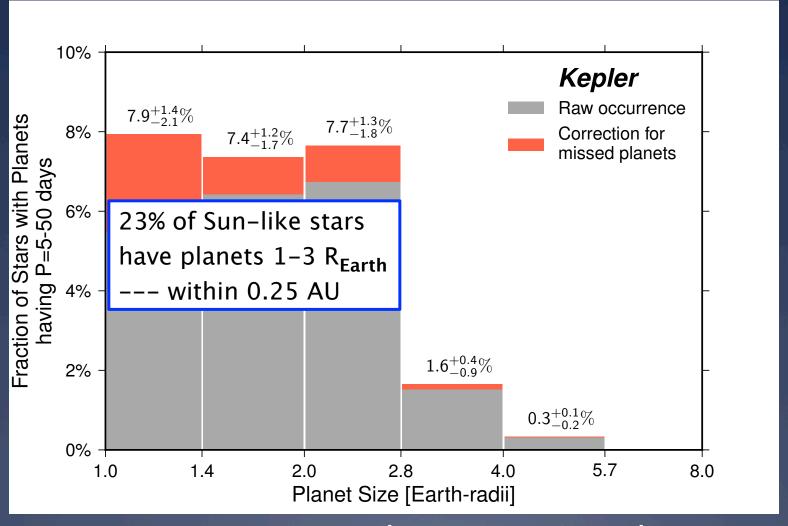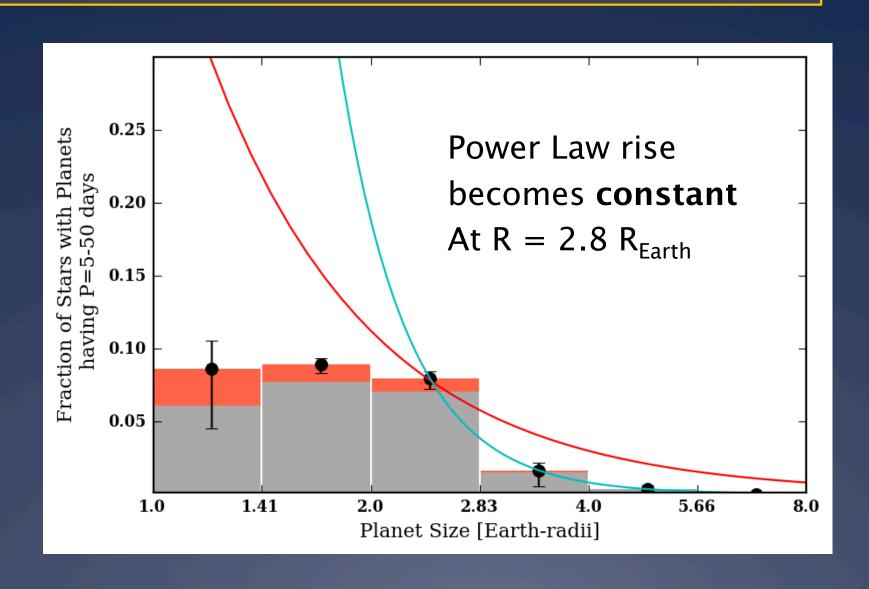Erik Petigura & Andrew Howard

Occurrence with Planet Radius: Extension to 1.0 R$_{Earth}$
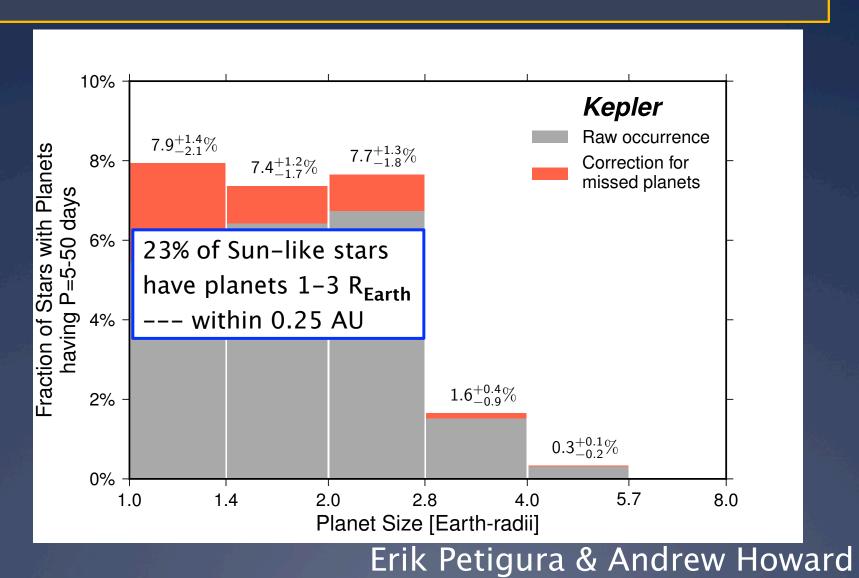
Erik Petigura & Andrew Howard

Exoplanet Radius Distribution

Power Law rise becomes **constant** At R = 2.8 R$_{Earth}$

Occurrence with Planet Radius:
Extension to 1.0 R$_{Earth}$

Erik Petigura & Andrew Howard

Occurrence with Planet Radius
Fressin, Torres, Charbonneau:

Occurrence is
Flat Shortward
of 2 R_{Earth}
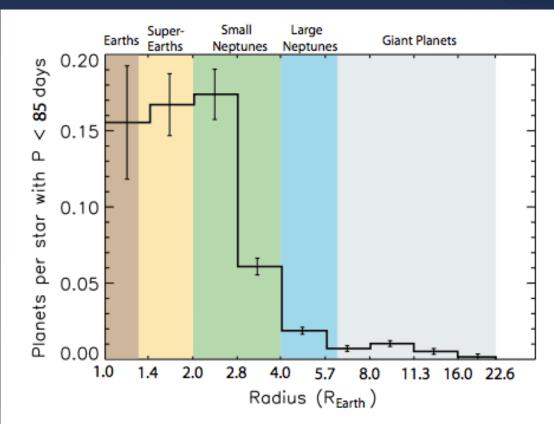
Agreement with
Petigura & Howard

FIG. 7.— Average number of planets per size bin for main sequence FGKM stars, determined here from the Q1–Q6 *Kepler* data and corrected for false positives and incompleteness.

FAST RISE OF "NEPTUNE-SIZE" PLANETS ($4-8R_\oplus$) FROM $P \sim 10$ TO ~ 250 DAYS – STATISTICS OF *KEPLER* PLANET CANDIDATES UP TO ~ 0.75AU

SUBO DONG[1] AND ZHAOHUAN ZHU[2]
Draft version December 21, 2012

ABSTRACT

We infer period (P) and size (R_p) distribution of *Kepler* transiting planet candidates with $R_p \geq 1R_\oplus$ and $P < 250$ d hosted by solar-type stars. The planet detection efficiency is computed by using measured noise and the observed timespans of the light curves for $\sim 120,000$ *Kepler* target stars. Given issues with the parameters of *Kepler* host stars and planet candidates (especially the unphysical impact parameter distribution reported for the candidates), we focus on deriving the shape of planet period and radius distribution functions. We find that for orbital period $P > 10$ d, the planet frequency $dN_p/d\log P$ for "Neptune-size" planets ($R_p = 4-8R_\oplus$) increases with period as $\propto P^{0.7\pm0.1}$. In contrast, $dN_p/d\log P$ for "Super-Earth-Size" ($2-4R_\oplus$) as well as "Earth-size" ($1-2R_\oplus$) planets are consistent with a nearly flat distribution as a function of period ($\propto P^{0.11\pm0.05}$ and $\propto P^{-0.10\pm0.12}$, respectively), and the normalizations are remarkably similar (within a factor of ~ 1.5). The shape of the distribution function is found to be not sensitive to changes in selection criteria of the sample. The implied nearly flat or rising planet frequency at long period appears to be in tension with the sharp decline at ~ 100 d in planet frequency for low mass planets (planet mass $m_p < 30M_\oplus$) recently suggested by HARPS survey.

FAST RISE OF "NEPTUNE-SIZE" PLANETS ($4-8R_\oplus$) FROM $P \sim 10$ TO ~ 250 DAYS – STATISTICS OF *KEPLER* PLANET CANDIDATES UP TO ~ 0.75AU

SUBO DONG[1] AND ZHAOHUAN ZHU[2]

Draft version December 21, 2012

ABSTRACT

We infer period (P) and size (R_p) distribution of *Kepler* transiting planet candidates with $R_p \geq 1R_\oplus$ and $P < 250$ d hosted by solar-type stars. The planet detection efficiency is computed by using measured noise and the observed timespans of the light curves for $\sim 120,000$ *Kepler* target stars. Given issues with the parameters of *Kepler* host stars and planet candidates (especially the unphysical impact parameter distribution reported for the candidates), we focus on deriving the shape of planet period and radius distribution functions. We find that for orbital period $P > 10$ d, the planet frequency $dN_p/d\log P$ for "Neptune-size" planets ($R_p = 4-8R_\oplus$) increases with period as $\propto P^{0.7\pm0.1}$. In contrast, $dN_p/d\log P$ for "Super-Earth-Size" ($2-4R_\oplus$) as well as "Earth-size" ($1-2R_\oplus$) planets are consistent with a nearly flat distribution as a function of period ($\propto P^{0.11\pm0.05}$ and $\propto P^{-0.10\pm0.12}$, respectively), and the normalizations are remarkably similar (within a factor of ~ 1.5). The shape of the distribution function is found to be not sensitive to changes in selection criteria of the sample. The implied nearly flat or rising planet frequency at long period appears to be in tension with the sharp decline at ~ 100 d in planet frequency for low mass planets (planet mass $m_p < 30M_\oplus$) recently suggested by HARPS survey.

For R = 1–4 REarth: dNp/dlogP ~ Constant

Exoplanets:
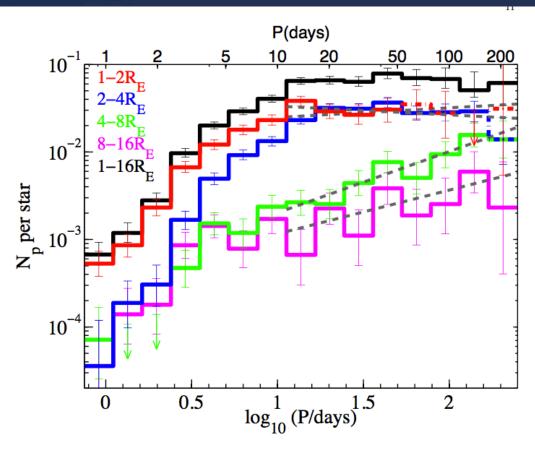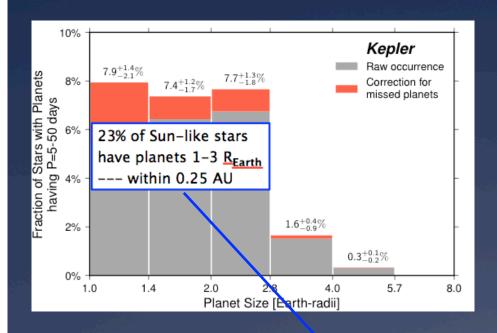## Distribution of Orbital Periods

FIG. 7.— The intrinsic number of planets per star at different planet radius and period bins plotted as a function of period. The histograms with error bars in various colors represents different planet-radius bins (red: $1-2R_\oplus$, blue: $2-4R_\oplus$, green: $4-8R_\oplus$, magenta: $8-16R_\oplus$, black: $1-16R_\oplus$). The dotted-dash part of the histograms are for the bins with the least secure statistics, corresponding to the bins marked with small grids in Fig. and the statistics in those bins are the least trustworthy. The maximum likelihood best fits in power-law distribution as a function of period for planets beyond 10 days at each planet radius bin are over plotted as the grey dashed lines. For orbital period $P > 10$ d, the planet frequency $dN_p/d\log P$ for "Neptune-size" planets ($R_p = 4-8R_\oplus$) increases with period as $\propto P^{0.7\pm0.1}$. In contrast, $dN_p/d\log P$ for "Super-Earth-Size" ($2-4R_\oplus$) as well as "Earth-size" ($1-2R_\oplus$) planets are consistent with a nearly flat distribution as a function of period ($\propto P^{0.11\pm0.05}$ and $\propto P^{-0.10\pm0.12}$, respectively), and the normalizations are remarkably similar (within a factor of ~ 1.5). Detailed discussion see § 4.1

For R = 1–4 R_{Earth}:
$dN_p/d\log P \sim$ Constant

Kepler planets through Q6

Dong & Zhu (2013)

Occurrence with Planet Radius:
Extension to 1.0 R_{Earth}
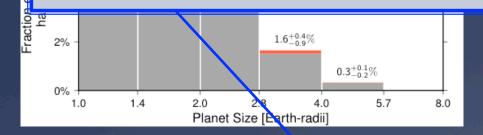
For R = 1–4 R_{Earth}:
$dN_p/dlogP \sim$ Constant

45% of Sun–like stars have planets 1–3 R_{Earth} between Period = 5 – 500 days.

Science Case for
NRO 2.4-m Coronagraph:

45% of Sun-like stars have 1-3 R_{Earth} planets within 1.2 AU

Fraction of Stars with Planets

2% $1.6^{+0.4}_{-0.9}\%$ $0.3^{+0.1}_{-0.2}\%$

0% 1.0   1.4   2.0   2.8   4.0   5.7   8.0
Planet Size [Earth-radii]

45% of Sun–like stars have planets 1–3 R_{Earth} between Period = 5 – 500 days.

Coronagraph Progress

* At JPL, in the original High Contrast Imaging Testbed (HCIT-1), Gene Serabyn obtained narrow-band contrasts less than 1 x 10-9 with the vector vortex coronagraph.

* In the new HCIT-2, and also in narrow-band light, Olivier Guyon,and collaborators reached 6 x 10-10 with the Phase Induced Amplitude Apodization (PIAA) coronagraph.

* Mark Clampin at NASA/GSFC reached 3 x 10-9 contrast monochromatically with the Visible Nulling Coronagraph. These each represent about an order of magnitude improvement in performance over where they were a year ago.

ExO: The Exoplanet Observatory
Astrophysics

Overview

POC: Gary Blackwood, Exoplanet Exploration Program
gary.h.blackwood@jpl.nasa.gov   818-354-6263

Key collaborators: Exoplanet Exploration Program Office and list of supporting individuals.

Goals: The prime objective of the *Exoplanet Observatory* will be to provide a detailed portrait of exoplanets around our nearest F, G, K, and M stars. *ExO* will operate at visible and near-infrared wavelengths to directly image gas/ice giants down to the largest of terrestrial planets. *ExO* will measure their spectra and determine their orbits. It will image debris disks and characterize exozodiacal dust. *ExO* complements this data through astrometry to measure exoplanet masses and orbits, and through spectroscopy to study large transiting planets close to their stars.

ExO's General Observer Program will provide new opportunities for NASA Cosmic Origins science and Planetary Science.
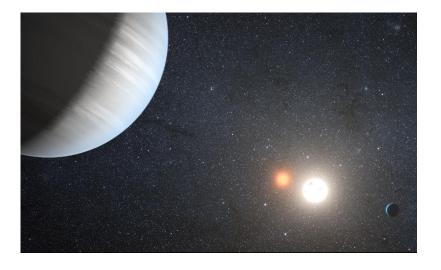
Description

Instruments:

- High-contrast coronagraph with Integral Field Spectrograph, imaging over 0.4-1.0 µm, at 10% bandwidths, with working angles of 3-60 λ/D, 10^{-9} contrast (baseline) and 10^{-10} (goal) post-processed, with 8x8 arcsec FOV, spatial resolution 0.05 arcsec, and R = 70
- Astrometric Imaging Camera with 3 x 3 arcmin FOV
- Time-resolved Spectrometer observing 0.8-2.4 µm, R=1000

Operations: From a Sun-Earth L-2 orbit, the observatory will sequentially observe accessible nearest-neighbor F, G, K, and selected M stars once per quarter, with direct imaging and astrometry. Transit spectroscopy will be used for appropriate targets.

Opportunities:

- Leverages and complements ground-based radial-velocity observations

Human exploration: The observatory will be designed for robotic servicing

Value to NASA

Advances the Priorities of NASA's Astrophysics Division

- *ExO* addresses New Worlds, New Horizons 2010 #1 medium-scale recommendation for a New Worlds Technology Development Program to address "*preparation for a planet-imaging mission beyond 2020, including precursor science activities*" (p. ES-6).
- *ExO* addresses NWNH 2010 small-scale recommendation "*understanding the birth of galaxies, stars, and planets*" (p. ES-4).

Advances Technology highlighted by NASA's Space Technology Mission Directorate

- Advances high-contrast imaging and spectroscopy technology
- Prepares NASA for a later mission to image Earths and search for signs of life.

Provides Education and Public Outreach opportunities tied to the exploration for life in our galactic neighborhood.

ExO: The Exoplanet Observatory
Astrophysics

Overview

POC: Gary Blackwood, Exoplanet Exploration Program
gary.h.blackwood@jpl.nasa.gov   818-354-6263

Key collaborators: Exoplanet Exploration Program Office and list of supporting individuals.

Goals: The prime objective of the *Exoplanet Observatory* will be to provide a detailed portrait of exoplanets around our nearest F, G, K, and M stars. *ExO* will operate at visible and near-infrared wavelengths to directly image gas/ice giants down to the largest of terrestrial planets. *ExO* will measure their spectra and determine their orbits. It will image debris disks and characterize exozodiacal dust. *ExO* complements this data through astrometry to measure exoplanet masses and orbits, and through spectroscopy to study large transiting planets close to their stars.

ExO's General Observer Program will provide new opportunities for NASA Cosmic Origins science and Planetary Science.

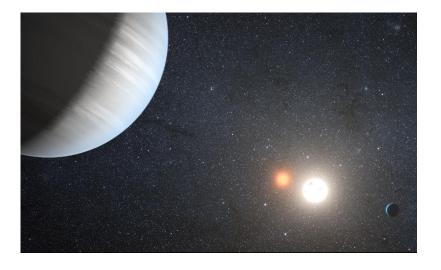## Description

Instruments:
- High-contrast coronagraph with Integral Field Spectrograph, imaging over 0.4-1.0 µm, at 10% bandwidths, with working angles of 3-60 λ/D, 10^{-9} contrast (baseline) and 10^{-10} (goal) post-processed, with 8x8 arcsec FOV, spatial resolution 0.05 arcsec, and R = 70
- Astrometric Imaging Camera with 3 x 3 arcmin FOV
- Time-resolved Spectrometer observing 0.8-2.4 µm, R=1000

Operations: From a Sun-Earth L-2 orbit, the observatory will sequentially observe accessible nearest-neighbor F, G, K, and selected M stars once per quarter, with direct imaging and astrometry. Transit spectroscopy will be used for appropriate targets.

Opportunities:
- Leverages and complements ground-based radial-velocity observations

Human exploration: The observatory will be designed for robotic servicing

Value to NASA

Advances the Priorities of NASA's Astrophysics Division
- *ExO* addresses New Worlds, New Horizons 2010 #1 medium-scale recommendation for a New Worlds Technology Development Program to address "*preparation for a planet-imaging mission beyond 2020, including precursor science activities*" (p. ES-6).
- *ExO* addresses NWNH 2010 small-scale recommendation "*understanding the birth of galaxies, stars, and planets*" (p. ES-4).

Advances Technology highlighted by NASA's Space Technology Mission Directorate
- Advances high-contrast imaging and spectroscopy technology
- Prepares NASA for a later mission to image Earths and search for signs of life.

Provides Education and Public Outreach opportunities tied to the exploration for life in our galactic neighborhood.

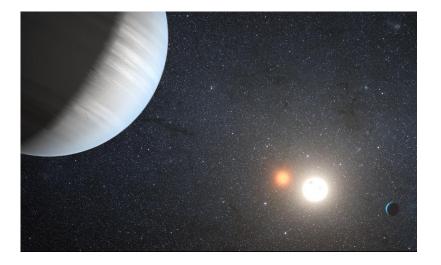# *ExO:* The Exoplanet Observatory
Astrophysics

Overview

POC: Gary Blackwood, Exoplanet Exploration Program
gary.h.blackwood@jpl.nasa.gov   818-354-6263

Key collaborators: Exoplanet Exploration Program Office and list of supporting individuals.

Goals: The prime objective of the *Exoplanet Observatory* will be to provide a detailed portrait of exoplanets around our nearest F, G, K, and M stars. *ExO* will operate at visible and near-infrared wavelengths to directly image gas/ice giants down to the largest of terrestrial planets. *ExO* will measure their spectra and determine their orbits. It will image debris disks and characterize exozodiacal dust. *ExO* complements this data through astrometry to measure exoplanet masses and orbits, and through spectroscopy to study large transiting planets close to their stars.

ExO's General Observer Program will provide new opportunities for NASA Cosmic Origins science and Planetary Science.

Description

Value to NASA

Instruments:

- High-contrast coronagraph with Integral Field Spectrograph, imaging over 0.4-1.0 μm, at 10% bandwidths, with working angles of 3-60 λ/D, 10^{-9} contrast (baseline) and 10^{-10} (goal) post-processed, with 8x8 arcsec FOV, spatial resolution 0.05 arcsec, and R = 70

- Advances high-contrast imaging and spectroscopy technology
- Prepares NASA for a later mission to image Earths and search for signs of life.

Provides Education and Public Outreach opportunities tied to the exploration for life in our galactic neighborhood.

Opportunities:
- Leverages and complements ground-based radial-velocity observations

Human exploration: The observatory will be designed for robotic servicing

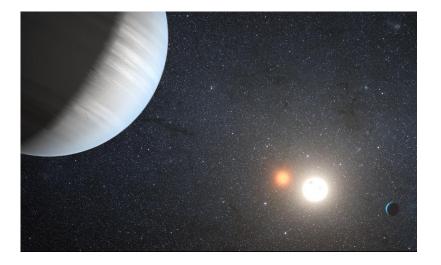# *ExO:* The Exoplanet Observatory
Astrophysics

Overview

POC: Gary Blackwood, Exoplanet Exploration Program
gary.h.blackwood@jpl.nasa.gov   818-354-6263

Key collaborators: Exoplanet Exploration Program Office and list of supporting individuals.

Goals: The prime objective of the *Exoplanet Observatory* will be to provide a detailed portrait of exoplanets around our nearest F, G, K, and M stars. *ExO* will operate at visible and near-infrared wavelengths to directly image gas/ice giants down to the largest of terrestrial planets. *ExO* will measure their spectra and determine their orbits. It will image debris disks and characterize exozodiacal dust. *ExO* complements this data through astrometry to measure exoplanet masses and orbits, and through spectroscopy to study large transiting planets close to their stars.

ExO's General Observer Program will provide new opportunities for NASA Cosmic Origins science and Planetary Science.

Description

Instruments:

- High-contrast coronagraph with Integral Field Spectrograph, imaging over 0.4-1.0 μm, at 10% bandwidths, with working angles of 3-60 λ/D, 10^{-9} contrast (baseline) and 10^{-10} (goal) post-processed, with 8x8 arcsec FOV, spatial resolution 0.05 arcsec, and R = 70

Opportunities:
- Leverages and complements ground-based radial-velocity observations

Human exploration: The observatory will be designed for robotic servicing

Value to NASA

- Advances high-contrast imaging and spectroscopy technology
- Prepares NASA for a later mission to image Earths and search for signs of life.

Provides Education and Public Outreach opportunities tied to the exploration for life in our galactic neighborhood.

AFTA Potential High-Contrast Science

Jeremy Kasdin
Bruce Macintosh, Dmitry Savransky, Karl Stapelfeld,
Aki Roberge, Olivier Guyon, Glenn Schneider, Marshall Perrin

Baseline Assumption:

A robust coronagraph at 10^{-8} to 10^{-9} contrast with 3 to 3.5 lambda/D inner working angle at 800 nm and 20% to 50% throughput.

That performance level should be achievable with current technology.

AFTA Potential High-Contrast Science

Jeremy Kasdin
Bruce Macintosh, Dmitry Savransky, Karl Stapelfeld,
Aki Roberge, Olivier Guyon, Glenn Schneider, Marshall Perrin

Exoplanet Imaging and Spectroscopy

○ Gas and ice giant exoplanet detection & characterization

1. Visible colors of some RV and GPI/SPHERE planets
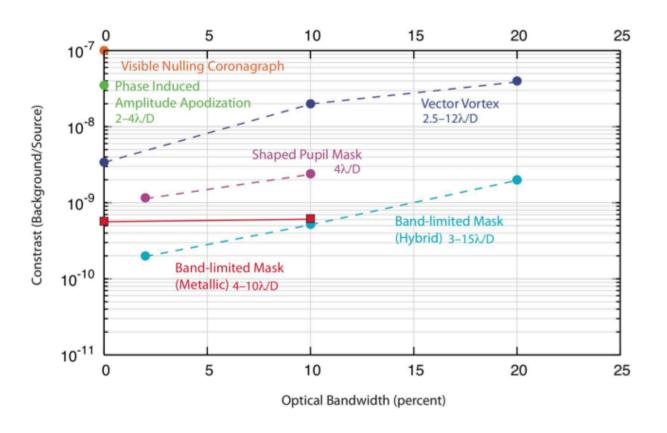2. Optical spectra of brightest detected planets = comparative planetology
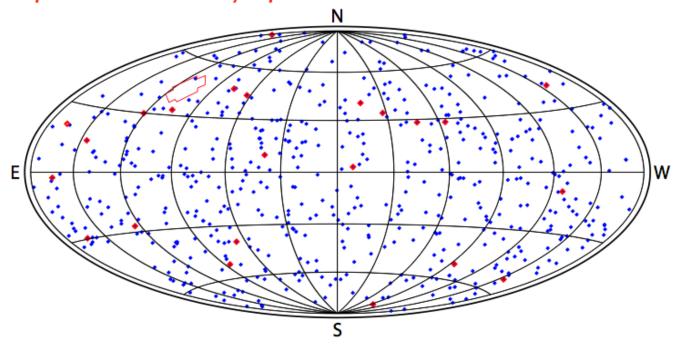
Consistent with Small Explorer Science Mission.

– Exoplanet Coronagraphy –
An Essential Synergy with the WFIRST Mission

John Trauger – JPL/Caltech
Princeton NRO Telescope Workshop
6 September 2012

Laboratory Demonstrated Coronagraph Performance

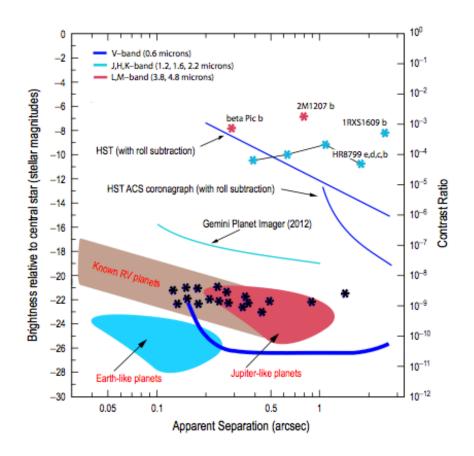Data compiled by Peter Lawson (Jan 2012)

Exoplanet Discovery Space: the nearest 600 AFGK stars

- In blue, a sky map of the Sun-like FGK type stars to distances of 20 parsecs from the Earth.
- In red, the 23 stars known to have at least one Jovian planet with an orbital separation greater than 100 milliarcseconds as seen from the Earth (21 by radial velocities, plus beta-Pic and HR8799).
- These RV systems, yet to be seen in direct images, are leading candidates for coronagraphic imaging and spectroscopy at visible wavelengths in reflected starlight.
- The irregular red box at upper left is the Kepler field of 100,000 distant stars.

Thanks to J.Trauger

Exoplanet Imaging Discovery Space
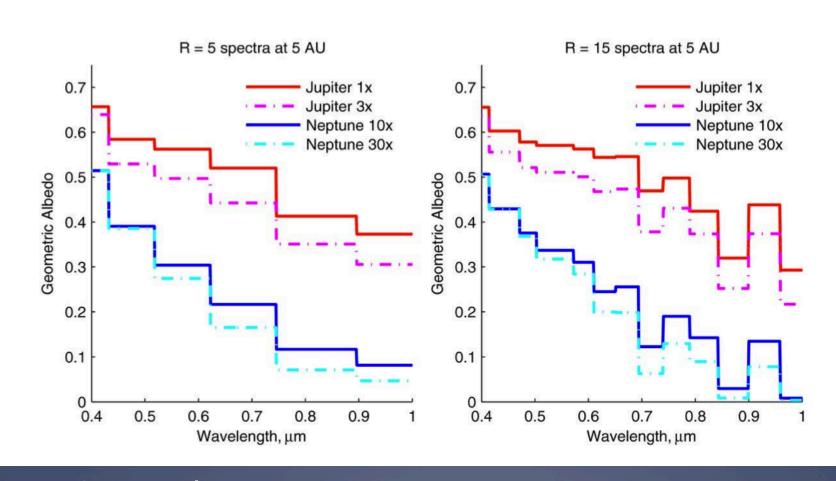## – from the ACCESS study –

- Imaging performance based on the ACCESS concept study (JPL 2009), a 1.5 meter space observatory.
- Blue curve is the sensitivity based on the demonstrated performance of the hybrid Lyot coronagraph.
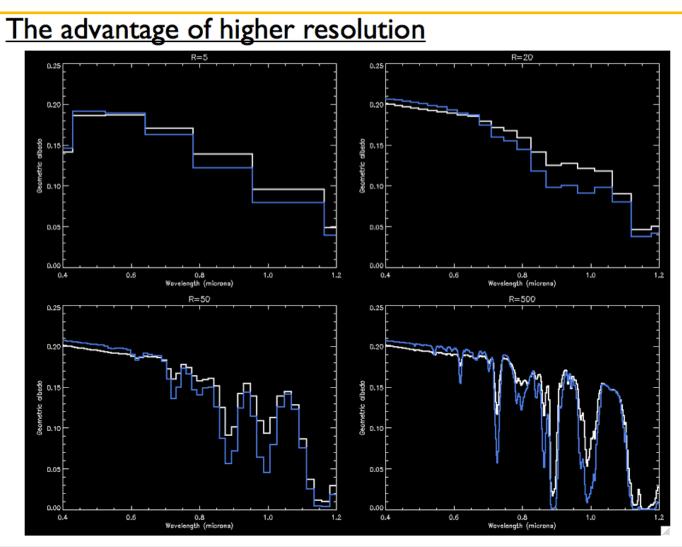- Asterisks indicate known planets.

J.Trauger

AFTA-WFIRST Spectroscopy:
Measuring Metalicity of Exoplanets

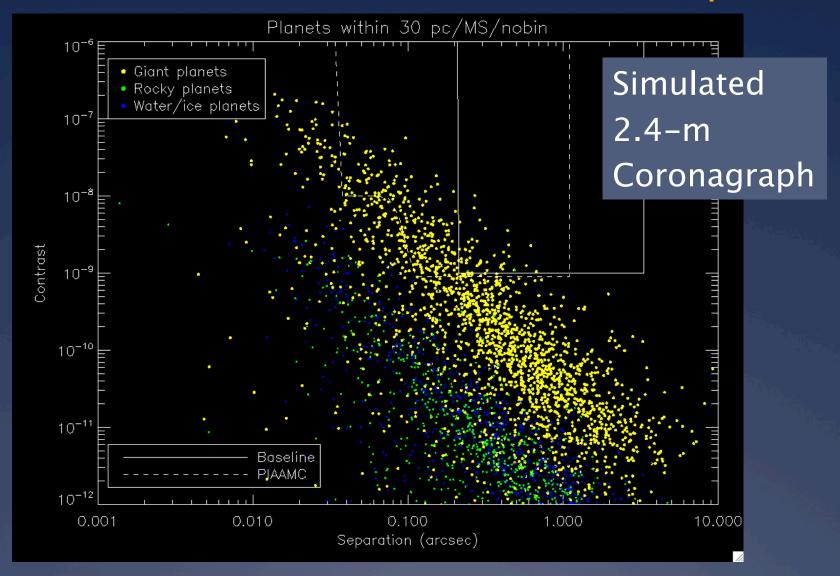for Jupiter and Neptune analogs at 5 AU and different metallicities

Cahoy, Marley, Fortney,
With thanks to Bruce Macintosh & Jeremy Kasdin

AFTA-WFIRST Spectroscopy:
Measuring Metalicity of Exoplanets

Kerry Cahoy, Mark Marley, Jonathan Fortney Models.
Thanks to J.Kasdin and B.Macintosh

Simulated Planets within 30pc

Simulated 2.4-m Coronagraph

Thanks so Bruce Macintosh

Summary: NRO Coronagraph

- ~50% of Sun-like stars have 1–3 R_{Earth} planets within 1.2 AU (Kepler)

  - 10 pc sample of 100 FGKM stars:
    5 AU → 0.5 arcsec : Imaging with coronagraph possible.

  - Nearest stars are packed with
    many 1–3 R_{Earth} planets within 0.5 arcsec.

Summary:
NRO Coronagraph
For AFTA–WFIRST

Needed:
  1. Design Studies of Coronagraphs, and lab tests. Funding Needed.

  2. Assessment of NRO telescope optical performance: PSF, stability

  3. Predict planets around 5pc stars, given Kepler and Doppler planet
       occurrence rates.

  4. AFTA–WFIRST Coronagraph:
        Consistent with 2010 Decadal Survey

* Concept submission to SALSO (judged Jan 7):

* At least one exoplanet concept will go forward.

* Ground RV will complement EXO. Would advocate for a strong ground-based RV program.

* Should we include the starshade, or just make it "star-shade ready".

* Wes Traub and Rachel Akeson are leaders.

* Kasting, Quirrenbach, Lissauer, W.Cash, Polidan, Boss, Rieke, Ben Lane, Alycia Weinberger, Nikole Lewis, Geoff Bryden, Rob Eggerman. Avi Mandell (goddard).

* Nick Gautier, Jeremy kasdin, Marie Levine, Unwin, Traub,

* Wes Traub: FGKM nearest stars

* Works in visible and IR, and doesn imaging and astrometry. Follows "SPOTS" get sub-microarcsecond astrometry from Guyon. P < 5 yr (inner orbits). P > 5 yrs (done by imaging).

* Do narrow field and wide field simultaneously, using a "little hole".

* Imaging: outer HZ outward, assuming 2.4-m telescope.

* Achieves contrast of 10^-10, and will get 4 lambda/d.

ExO: The Exoplanet Observatory ········ **DRAFT**

Gary Blackwood (PM, Exoplanet Exploration Program), Gary.H.Blackwood@jpl.nasa.gov
and xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
Xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
(please let us know if you would like to be listed as a contributor)
Xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

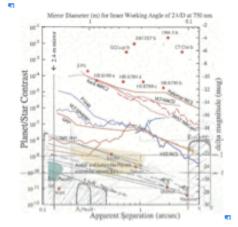══════════ Section Break (Continuous) ══════════

Category: Astrophysics

Summary

The Exoplanet Observatory (*ExO*) is an observatory dedicated to exoplanet science, focusing on exoplanets orbiting our nearest neighbor stars. *ExO* will observe from a Sun-Earth L-2 orbit, with a 5-year baseline mission, and designed for robotic servicing. *ExO* will search for gas giant, ice giant, and superEarth exoplanets and debris discs around the nearest F, G, K, and selected M stars with high-contrast imaging and spectroscopy. Astrometric observations will discover and provide exoplanet masses. Near-infrared transit spectroscopy will enable observations of known nearby transiting objects, potential M-star transits, and more distant exoplanets. *ExO* leverages and complements ground-based radial-velocity surveys. ExO employs a dual-instrument mode of observing, giving twice the data rate compared to a mission with only one instrument mode at a time. And the science return is magnified further by the specific choices of instruments, one to discover and characterize a bright target star system, and a parallel one to measure the transverse motion of that same star, giving masses and orbits of the planets. The suite of instruments will enable a comprehensive General Observer (GO) program, and provide opportunities in planetary science for objects within our own outer Solar System.

Science Goal of *ExO*

The goal of *ExO* is to advance exoplanet science toward the long-term objective of finding life elsewhere in the Universe. *ExO* will be able to detect and characterize superEarths in the outer habitable zone around the very nearest stars. It will detect and characterize debris disks and large planets in orbits beyond the habitable zone. Zodiacal dust discs about ten times brighter than ours will be detectable around the nearest stars. *ExO* will produce an inventory of larger planets around stars in the Solar neighborhood. These systems will become high priority targets in our future search for Earth-like planets and life.

Figure 4 - *ExO* will directly image and characterize gas giants, ice giants, debris disks, and superEarths around nearby F, G, K, and selected M stars. The science requires a coronagraph with an inner working angle of 2λ/D or about 0.1 arcsec, astrometric astrometry of about 4D⁻⁶ post-processing, and an IFU with spectral resolution of about 70. *ExO* will detect planets and measure their masses with sub-micro-arcsec astrometry, which requires a wide field and a pattern of dots on the primary mirror. And *ExO* will characterize the atmospheres of transiting planets around known systems and potential nearby M stars with a 0.8 to 1.8 μm, R = 1000, spectrometer. **DRAFT FIGURE**

* I don't... e.

Benefits of *ExO*

ExO directly supports the goals and long-term objectives of the Exoplanet Exploration Program and NASA's Astrophysics Division.

It supports the *2011 NASA Strategic Plan*, goal 2.4, to "Discover how the universe works, explore how it began and evolved, and search for Earth-like planets." It supports NASA strategic objective 2.4.2, "Improve understanding of the many phenomena and processes associated with galaxy, stellar, and planetary system formation, and evolution from the earliest epochs to today". It also supports NASA strategic objective 2.4.3, "Generate a census of extra-solar planets and measure their properties". The same science objectives are emphasized and echoed in the NASA *2010 Science Plan*.

The science goals support the NRC 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH), which recommends advancing the technology and science of exoplanets this decade. Although only the tip of the Earth-like planet 'iceberg' will be detectable by *ExO*, its capabilities will enable a whole new era of exoplanet exploration.

Architecture of *ExO*

Operations will be at Sun-Earth L-2 for maximum thermal stability and sky coverage. Instruments and spacecraft will be modular, for future robotic servicing. *ExO* leverages work done for the Astrophysics Focused Telescope Assets (AFTA) study. *ExO* has three instruments, described in science priority order.

I. High-Contrast Imaging Field Unit (IFU)

ExO will have a high-contrast coronagraph with an IFU imaging spectrometer focal plane. A coronagraph with selectable components would allow tuning the choice of instrument (e.g., apodized Lyot, hybrid band-limited Lyot, vector vortex) to match the target, since these designs differ in their contrast and inner working angle values. Two deformable mirrors are needed for wavefront control. A low-order wavefront sensor will provide fine guidance and low-order aberration suppression. The coronagraph feeds an Integral Field Unit (IFU), an imaging spectrograph with approximately 0.4-1.0 μm wavelength range, 10×10 arcsec field of view, 0.05 arcsec spatial resolution, and spectral resolution of about 70.

ExO will be starshade-compatible, with beacons and telemetry to guide formation-flying. In starshade-mode, the coronagraph will operate in a "straight-through" mode, with masks and stops removed. This allows *ExO* to operate at smaller inner working angles than would be possible with the coronagraph alone. *ExO* is designed to be starshade-compatible, with a separate launch for the starshade.

II. Astrometric Camera

The outer field of the image focused by the telescope will be sent to the astrometric camera, which measures exoplanet orbits and masses. The proposed implementation requires imprinting a 2-D grid of tiny dark spots on the primary mirror, to generate faint stellar diffraction spikes which map the star's location in the field at the sub-micro-arcsec level. This concept requires no moving parts, but it does require a wide field, hence a third powered optic, to give a 10 x 10 arcmin field of view.

III. Transit spectrometer

A visible near-infrared transit spectrometer completes the suite of instruments envisaged for *ExO*. The transit method delivers unique information about a planet's diameter, and its atmospheric absorption spectrum, giving physical conditions and chemical composition. The transit technique is especially useful for short-period planets because these are close to their star and have a greater chance of transiting. Since M stars are more abundant than FGK stars, and close-in transits of M stars

* I do

ExO: The Exoplanet Observatory

will give a higher signal-to-noise ratio than transits of later-type stars, this instrument will be ready for characterizing these events. The observatory will likely operate at 250 K or above, allowing wavelengths up to the thermal cutoff, so a spectral range 0.8–2.4 μm, and a resolution of $R = 1000$, will allow molecular bands of CH_4, H_2O, NH_3, collision-induced H_2, and other species to be observed.

Mission Design

ExO can be launched into an Earth-Sun L-2 orbit using an EELV launch vehicle, which provides a total payload mass of about 5000 kg. A total of 3200 kg is allocated to: the telescope system, spacecraft bus, including propulsion for orbit insertion and station-keeping at L-2, telecom (up to 100 Mbps using the Deep Space Network), power system (solar panels providing about 3kW plus batteries), attitude control system (assuming HST-class pointing requirements), and thermal control. The EELV would provide approximately 1800 kg for the instruments, accommodating the three instruments described above and potentially a fourth.

Astrophysical Example Programs

Cosmic Origins Science

As examples of Cosmic Origins observations that could be pursued, ExO could give narrow-field imaging of Active Galactic Nuclei with the coronagraph IFU (in straight-through mode), and wide-field, broad-band imaging of targets of opportunity with the astrometric camera (e.g., using HST-like filters).
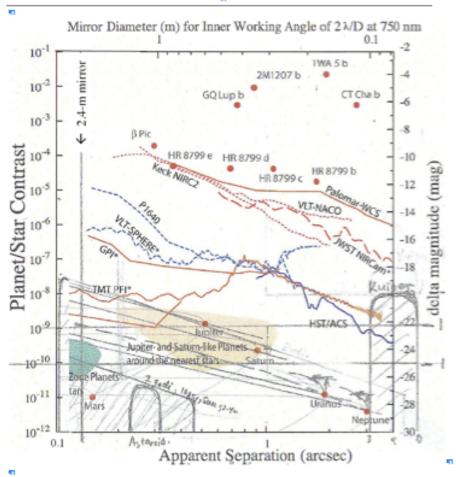
Planetary Science:

As examples of Planetary Science observations, ExO could monitor seasonal atmospheric changes of planets and moons in the outer Solar System using the coronagraph IFU (straight through), and molecular abundances using the medium-resolution, near-infrared spectrograph.
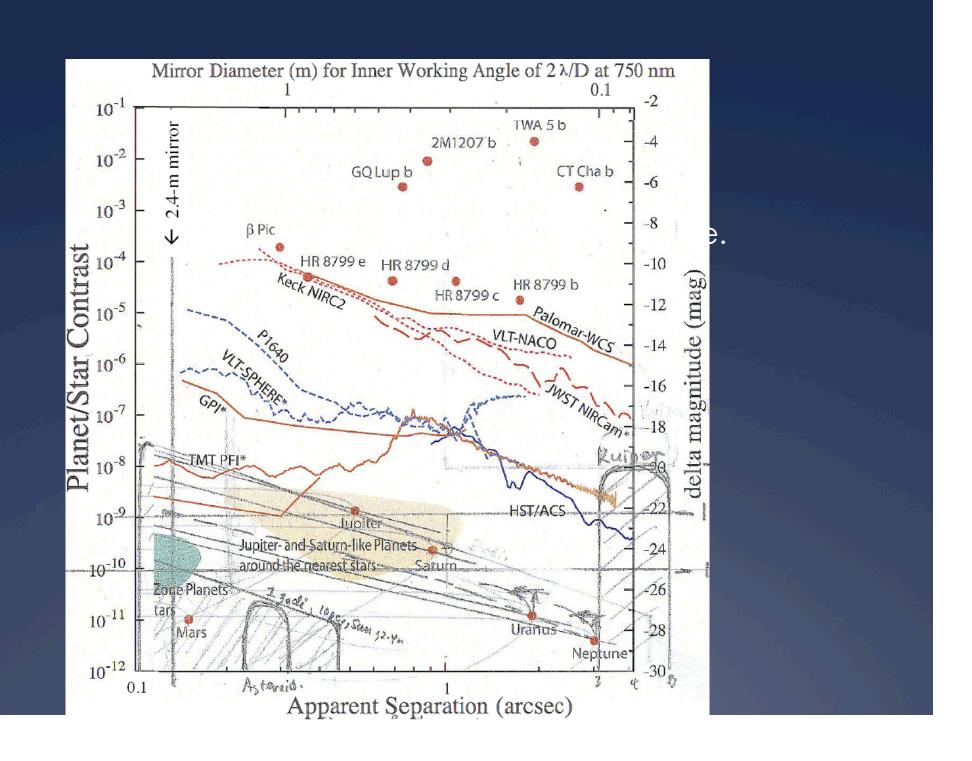
Anticipated Results:

ExO's dual-instrument observing mode delivers twice the science of a mission with either instrument alone. Thus ExO is perfectly suited to a discovery type of mission, where we are learning about phenomena for the first time, around stars that are close enough that follow-up observations, including a future dedicated terrestrial planet mission, can take advantage of the brightness and relatively accessible angular scales involved. Even taken alone, ExO will deliver an enormous science harvest, owing to its dual-instrument design, and its focus on nearby ssytems. ExO will discover and characterize large outer planets, large terrestrial planets, bright exozodiacal discs, and outer debris discs around the nearest-neighbor F, G, K and selected M stars. ExO will characterize the atmospheres of nearby transiting exoplanets, including M-star transits yet to be discovered. ExO will give us vastly more knowledge about our nearest-neighbor planetary systems, and prepare us for a future direct imaging mission capable of discovering Earth-size planets and searching for signs of life.

Section Break (Continuous)

ExO: The Exoplanet Observatory

This chart is enlarged only for purpose of the ExO telecon briefing. The concept paper will only show the smaller Figure 1.

* The Wide-Field Infrared Survey Telescope (WFIRST) is the top-ranked large space mission from the Astro2010 Decadal Survey. NASA is conducting a formulation phase study of design reference missions that would address essential questions in the areas of exoplanets, dark energy and infrared astrophysics.WFIRST will survey thousands of square degrees to AB~27 and make precision measurements of hundreds of millions of galaxies.

* A census will be performed of thousands of exoplanets from habitable Earth-mass planets to free floaters. An optional coronagraph will provide direct imaging of Jupiter-mass planets and debris disks. A Guest Observer program will offer community science for broad areas of science including cosmology, galaxy formation, brown dwarf surveys and solar system studies.NASA has recently been given two 'Hubble class' 2.4m telescopes.

* This splinter meeting will explore options for using one of these telescopes for WFIRST. An update on in-progress studies by the WFIRST Science Definition Team (SDT) and Project office will be presented by SDT co-chairs David Spergel and Neil Gehrels and the possibility of adding an exoplanet coronagraph instrument will be discussed.

It does transits, astrometry, 10^-10 contrast.

Wings don't decline outward of 10^-10.

We routinely see that you get a flat, dark hole, by focussing on the speckles. 128x128 DM.
   We make them.

Lissauer: NRO has Wide field of view. But most science doesn't take advantage of this.

0.2 arcsec → only good for tau Ceti and epsilon Eri.

Cost of achieving 10^-10 in post-processing.

Goals of specific stars needed.

Outer planet around Tau Ceti is just detectable.

Can get to HZ in alpha Cen B, but must block alpha Cen A.

Inner working angle: Serabyn says we might do better than 4 lambda/d. This is like TPF-C.
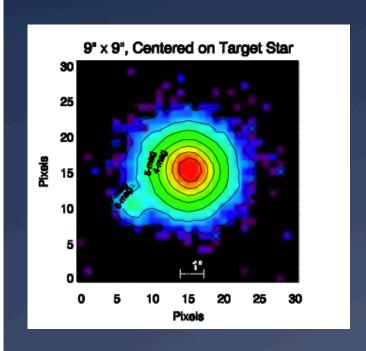
Geoff Bryden: Does doing astrometry affect high conrast imaging?
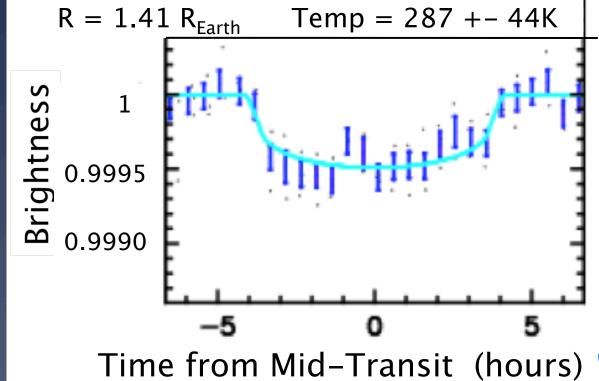
Maggie T.: 15 known exoplanets could be imaged, by using 4 lambda/d. (Jeremy wants it)

Question: does 10^-10 correspond to whole wavelength range?

Kepler is close to announcing two planets of ~1.5 REarth in the HZ

Planet in HZ:
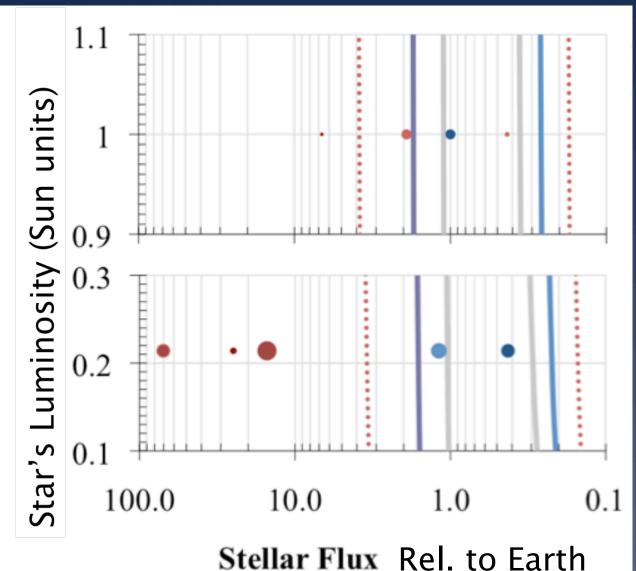Same Incident Flux as Earth,
R = 1.41 R$_{Earth}$

Orbital Period: 269 days
Orbital distance: 0.72 AU
Incident Stellar Flux: 0.45 x Solar flux at Earth
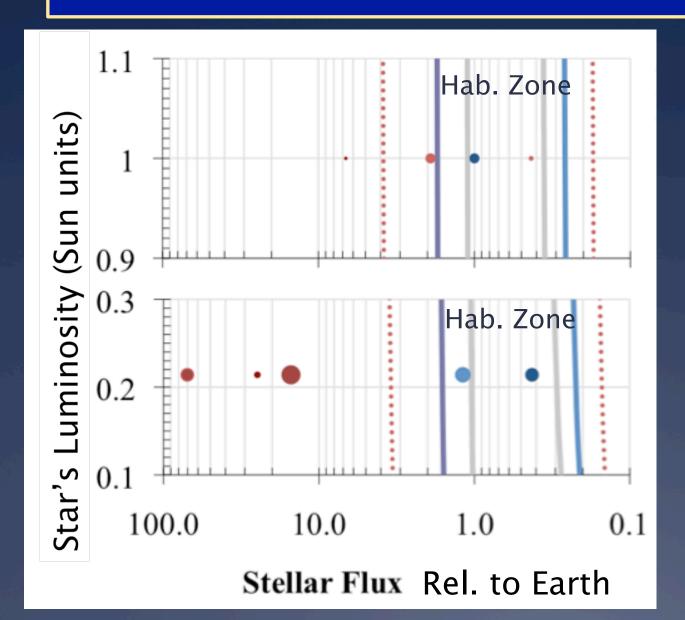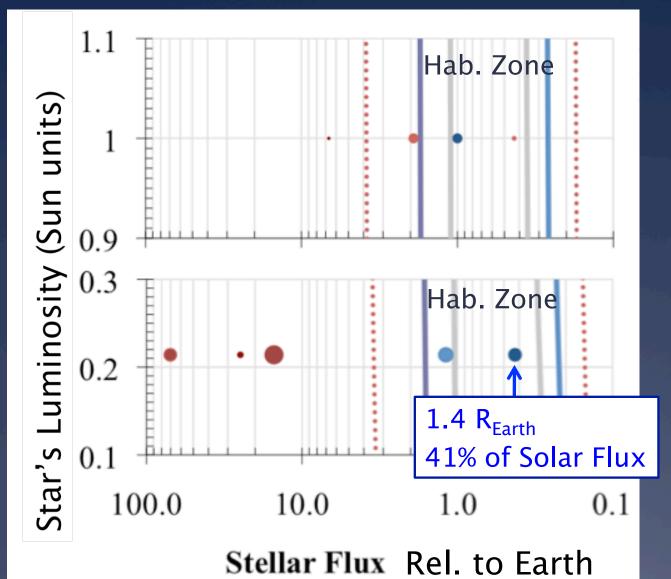
Incident Stellar Flux at Planets

Mercury
Venus
Earth
Mars

New Kepler
Planetary
System

Mass=0.69M$_{Sun}$

Incident Stellar Flux at Planets

Mercury
Venus
Earth
Mars
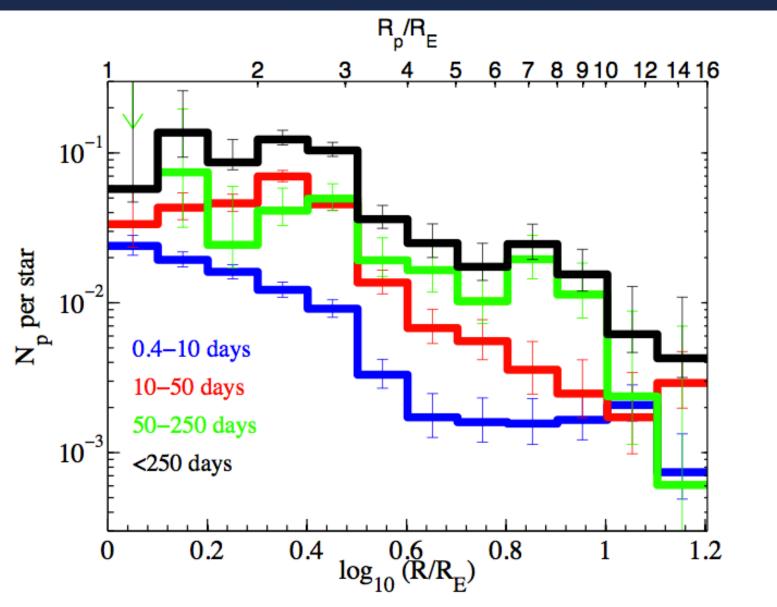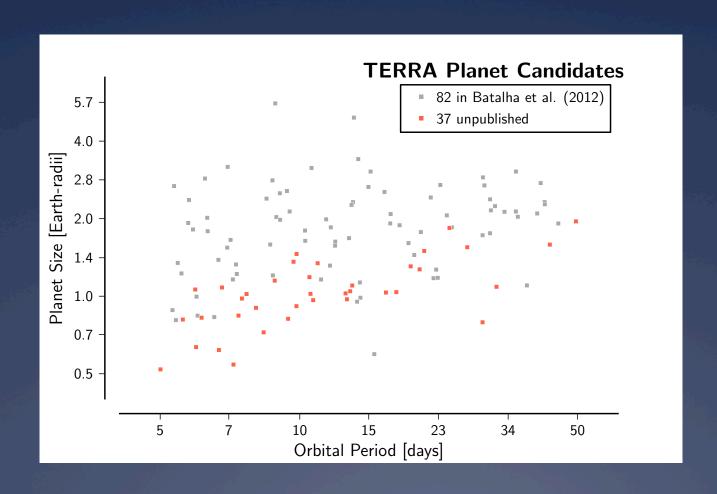
New Kepler
Planetary
System

Mass=0.69M$_{Sun}$

Incident Stellar Flux at Planets

FIG. 9.— The number of planet per star as a function of planet radii for planets at different period bins (blue: 0.4 – 10 days, red: 10 – 50 days, green: 50 – 250 days, black: < 250 days). There is considerable evolution in size distribution as a function of period. There seems to be clear breaks in the size distribution functions at 3 and 10 $R_{\oplus}$. The relative fraction of big planets at 3 – 10$R_{\oplus}$ compared to small planets (1 – 3$R_{\oplus}$) increase with period. Detailed discussion see § 4.1

Paul Hertz

* High budget: JWST highest priority.

* Budgetary future is uncertain.